PHYSICS OF SOLIDS IN INTENSE MAGNETIC FIELDS

Lectures presented at the First Chania Conference held at Chania, Crete, July 16-29, 1967

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PREFACE

Over one hundred scientists from a number of Western European countries, Australia, Canada, Israel, Japan, and the United States gathered on the island of Crete to discuss the physics of solids in intense magnetic fields. It was six years ago that many of the same participants were discussing the production and technology of high fields at the MIT Conference. This volume contains, in large measure, the proceedings of the Crete gathering.

The topics discussed during the first week were concerned mainly with electrons in Landau levels, with a number of comprehensive reviews; during the last part of the meeting many reports on the up-to-date progress in the field were presented. The subject matter began at a low level and rapidly proceeded to an advanced stage.

The opening lecture was given by E. Burstein on the interaction of electromagnetic waves with single-particle and collective excitations of free carriers in a magnetic field and on the measurement of these phenomena using infrared techniques and the photon–phonon interaction in the Raman effect. The quantum theory of electrons in crossed electric and magnetic fields, with emphasis on relativistic effects and on interband processes, was presented by W. Zawadzki. B. Lax discussed quantum magnetooptics, interband magnetoreflection and magnetoabsorption, cyclotron resonance, nonlinear multiple-photon effects, and other physical processes encountered in lasers in magnetic fields. A. B. Pippard explained his theory on magnetic breakdown involving cyclotron orbits in metals.

The lectures continued with G. Landwehr's talk on Shubnikov–de Haas and quantum-limit effects in semiconductors such as indium antimonide. Oscillatory effects were also discussed by Y. Shapira, who spoke on giant oscillations in ultrasonic attenuation in metals, such as gallium, and their use in Fermi–Dirac distribution functions, and on ultrasonic attenuation in type-II superconductors. W. L. McLean dealt with quantum oscillations in helicon propagation in tin. The magnetoquantum (photon) electric effects in solid-state plasmas, including the amplification phenomenon, were discussed by Y. Sawada.

The last speaker of the first week was J. Zak, who lectured on the application of group theory to a Bloch electron in a magnetic field. In a panel discussion B. Lax, E. Burstein, A. Pippard, and E. Haidemenakis reviewed the first week's subject matter and suggested areas of future research in the field.

The second week was devoted to more recent research in the field, which included superconductors, magnetospectroscopy, modulation techniques, magnetism, various magnetooptical effects, and recent methods in the production of very high magnetic fields. W. A. Runciman spoke on group theory and on the Zeeman effect in rare-earth-doped crystals. Lead salts and magnetooptical studies of band population effects were discussed by E. D. Palik. Some interesting modulation techniques were presented by J. Mavroides, who also illustrated his results in band structure studies. S. Williamson and E. Saur described various aspects of type-II superconductors, and N. Kurti talked about high magnetic fields and low temperatures. The topic of magnetism in ferro, antiferro, and ferri magnets was covered by S. Foncr.

Laser magnetospectroscopy and its application to the study of magnetooptical effects was discussed by S. Iwasa. P. R. Wallace developed a multicarrier model for the propagation of magnetoplasmas in semiconductors such as PbTe. Finally, the Faraday effect was discussed by G. Sacerdoti and by A. Van Itterbeek for pulsed fields. The last lectures were those of H. Knoepfel, who discussed megaoersted fields by implosion techniques, and A. Rabinovitch, who gave a seminar on the tight-binding approximation applied to a Bloch electron in a magnetic field. The lectures were reviewed by Professor Lax, who also gave the closing address of the meeting.

The directors of the Chania meeting were Pierre Aigrain of the Ecole Normale Supérieure, also Director of Higher Education in France, Eli Burstein of the University of Pennsylvania and Chairman of its Physics Department, and Benjamin Lax, Director of the National Magnet Laboratory at MIT. The chairman was Epimenides D. Haidemenakis of the Ecole Normale Supérieure and the Faculté des Sciences de Paris.

The sponsors of this meeting include: NATO Scientific Affairs Division, the Public Power Corporation of Greece, AGARD Greek Delegation, Greek Bureau of International Conventions, IBM World Trade Corporation, International Telephone and Telegraph Corporation, Hellenic Industrial Development Bank, Commercial Bank of Greece, Olympic Airways, Ionian and Popular Bank of Greece, Hellenic Electric Railways, Chandris Lines, National Organization of Greek Handicrafts, Telefunken, Efthimiades Lines, Agence Paris-Athenes, Phillips Greece, Metaxas Ouzo, Papastratos Cigarettes, K. Lampathakis, and Viochym Fruitjuice.

We wish to take this opportunity to extend once more our sincere gratitude to everyone involved in organizing this meeting. Above all we

wish to thank the Governor, the Mayor, the local authorities, Archbishop Irineos, the professional associations, the Ladies of Lykion, and all the people of Chania for the outstanding hospitality which they provided to the participants and their families.

E. D. Haidemenakis

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Chapter 1

THE INTERACTION OF ACOUSTIC AND ELECTROMAGNETIC WAVES ("SON ET LUMIÈRE") WITH PLASMAS IN A MAGNETIC FIELD*

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INTRODUCTION

In this chapter I will be concerned with the nature of the single-particle and collective excitations of plasmas in solids and their interactions with acoustic (A) waves and electromagnetic (E) waves in a magnetic field under conditions $\hbar\omega > \Delta\mathscr{E}$ and $\hbar q > \Delta p$, where $\Delta\mathscr{E} = \hbar/\Delta t$ is the uncertainty in the energy of the excitation and $\Delta p = \hbar/\Delta x$ is the uncertainty in the momentum of the excitation. Under these conditions the interactions can be treated semiclassically in terms of elementary processes in which (1) a phonon or photon of frequency ω and wave vector $\mathbf{q}$ is absorbed (or emitted) and an electron undergoes a transition from an initial state of energy $\mathscr{E}$ and wave vector $\mathbf{k}$ to a final (unoccupied) state of energy $\mathscr{E}' = \mathscr{E} + \hbar\omega$ and wave vector $\mathbf{k}' = \mathbf{k} + \hbar\mathbf{q}$ in the same Landau subband (a Landau transition) or in another Landau subband (a cyclotron transition); or (2) a phonon or photon is absorbed (or emitted) and a quantum of collective excitation of frequency $\Omega = \omega$ and wave vector $\mathbf{Q} = \mathbf{q}$ is created or annihilated. The investigation of the interactions of A and E waves with plasmas provides useful information about the nature of the single-particle and

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collective excitations of the plasma as well as about the energy band structure of semiconductors and the Fermi surface of metals.

The plasma is considered as an assembly of electrons (or holes) immersed in a uniform background of positive (or negative) charge whose density is equal to the average density of the electrons. In compensated plasmas the densities of the electrons and holes are equal and the background is considered to be neutral. We will be concerned primarily with plasmas which are degenerate, and which therefore have a Fermi surface. Since plasmas in solids at low temperatures are degenerate at relatively low charge carrier densities, this does not constitute a major limitation.

The physics underlying the interaction of A waves (phonons) and E waves (photons) with free carriers in the presence of an externally applied magnetic field have much in common, and the various magnetic–acoustical effects have their conterparts in magnetooptical effects. The difference in the two types of phenomena stem from (1) the considerable difference in the magnitude of the phonon–electron and photon–electron coupling constants, (2) the marked difference in the velocities and in the range of frequencies, and (3) the fact that A waves are "longitudinal" as well as "transverse," whereas E waves are "transverse."

The interactions of A and E waves with the single-particle and collective excitations take place via the electric fields of the waves. In the case of A waves the electric fields arise from the deformation potential (semiconductors and semimetals), the piezoelectric effect (semiconductors) and from induction effects (metals) ([1,2]). They are however much smaller than the electric fields of E waves, i.e., the energy of the A waves is predominantly mechanical. The magnitudes of the electric-dipole matrix elements are accordingly quite small. Consequently, the absorption of phonons by the free carrier excitations causes an attenuation of the waves but does not lead to any appreciable dispersion of the velocity of the waves. In the case of E waves the magnitude of the electric-dipole matrix elements are quite large, and the absorption of photons by the free carrier excitations produces strong anomalous dispersion effects. The frequency range of A waves is relatively small, and it is not possible to use A waves to investigate the collective excitations of a plasma except in the case of relatively low-density plasmas. On the other hand, there are excitations which interact with A waves but not with E waves—for example, Landau excitations in the Faraday configuration.

In the various discussions that follow the A and E waves will be assumed to be plane waves having a spatial and temporal dependence given by $\exp[i(\mathbf{q} \cdot \mathbf{r} - \omega t)]$. In addition, we make no distinction between RF, microwave, infrared, and visible frequencies since, apart from the differences in the experimental techniques that are required in the different frequency ranges, such distinctions do not, as such, enter into the underlying physics.

SINGLE-PARTICLE EXCITATIONS

Spherical Energy Bands

In the absence of a magnetic field the energy and wave function of an electron in a spherical energy band are given by

$$\mathscr{E}(\mathbf{k}) = \frac{\hbar^2(k_x^{\,2} + k_y^{\,2} + k_z^{\,2})}{2m^*} \tag{1a}$$

and

$$\psi_n(\mathbf{r}) = F_n(\mathbf{r})U_n(\mathbf{r}) = \exp[i(\mathbf{k} \cdot \mathbf{r})]U_n(\mathbf{r}) \tag{1b}$$

respectively, where $\hbar k_x$, $\hbar k_y$, and $\hbar k_z$ are the x, y, and z, components of the momentum of the electron; m^* is the effective mass of the electron; $U_n(\mathbf{r})$ is the Bloch function for the energy band n at $\mathbf{k} = 0$; and $F_n(\mathbf{r}) = \exp[i(\mathbf{k} \cdot \mathbf{r})]$ is the wave function of the free electron.

The energy levels of electrons in a magnetic field are discussed by Zawadzki in Chapter 13 of this volume. For a magnetic field $\mathbf{H}_0$ directed along the z axis the energy and wave function of the electron, neglecting spin, are given by

$$\mathscr{E}(L, k_z) = \hbar\omega_c(L + \tfrac{1}{2}) + \hbar^2 k_z^{\,2}/2m^* \tag{2a}$$

and

$$\psi_n(L, \mathbf{r}) = F_n(L, \mathbf{r})U_n(\mathbf{r}) = \exp[i(k_y y + k_z z)]\phi_L(x - x_0)U_n(\mathbf{r}) \tag{2b}$$

respectively where $\omega_c = eH_0/m^*c$ is the cyclotron frequency; L is the Landau quantum number; $x_0 = -(c\hbar/eH_0)k_y$ is the center of the cyclotron orbit along the x axis; and $\phi_L(x - x_0)$ is the harmonic oscillator function of the variable $(eH_0/c\hbar)^{1/2}(x - x_0)$. (The expression for $\psi_n(L, \mathbf{r})$ is based on the Landau (or asymmetric) gauge, $\mathbf{A} = [0, H_0 x, 0]$.) We note that the dependence of the energy on momentum involves only $\hbar k_z$, the component of the momentum along the magnetic field, and that the center of orbit is determined by $\hbar k_y$.

When the spin of the electron is taken into account the expression for the energy contains an additional term, $g\beta H_0\sigma$, where g is the effective g-factor, $\beta = e\hbar/2mc$ is the Bohr magneton, and $\sigma = \pm\frac{1}{2}$ is the z component of the spin angular momentum.

$$\mathscr{E}(L, k_z, \sigma) = \hbar\omega_c(L + \tfrac{1}{2}) + \frac{\hbar^2 k_z^{\,2}}{2m^*} + g\beta H_0\sigma \tag{3}$$

Similar expressions hold for the energy and the wave function of a hole in a spherical valence band.

The motion of the electron is quantized in the x–y plane and it is quasi-continuous in the z direction, the direction of the magnetic field. The energy levels form a series of "one-dimensional subbands" ([3]) (Fig. 1). Each energy level corresponds to a large number of degenerate states having different k_y values and therefore different centers of orbit. The degeneracy per unit area of the solid transverse to the magnetic field is equal to $(e\mathbf{H}_0/c\hbar)$.

The electrons are also characterized by an uncertainty in energy, $\Delta\mathscr{E} = \hbar/\tau(L, \mathbf{k}, \sigma)$ where $\tau(L, \mathbf{k}, \sigma)$ is the lifetime of the electron in the $(L, \mathbf{k}, \sigma)$ state, and by an uncertainty in momentum $\Delta k = 1/l(L, \mathbf{k}, \sigma)$ where $l(L, \mathbf{k}, \sigma)$ is the mean free path of the electron. For the purposes of the present discussion we will assume that $l(L, \mathbf{k}, \sigma) = v(L, \mathbf{k}, \sigma)\tau(L, \mathbf{k}, \sigma)$ where $v(L, \mathbf{k}, \sigma)$ is the velocity of the electron; namely, we assume that both $\Delta\mathscr{E}$ and $\Delta(\hbar k)$ are determined by the lifetime, $\tau(L, \mathbf{k}, \sigma)$. The wave func-

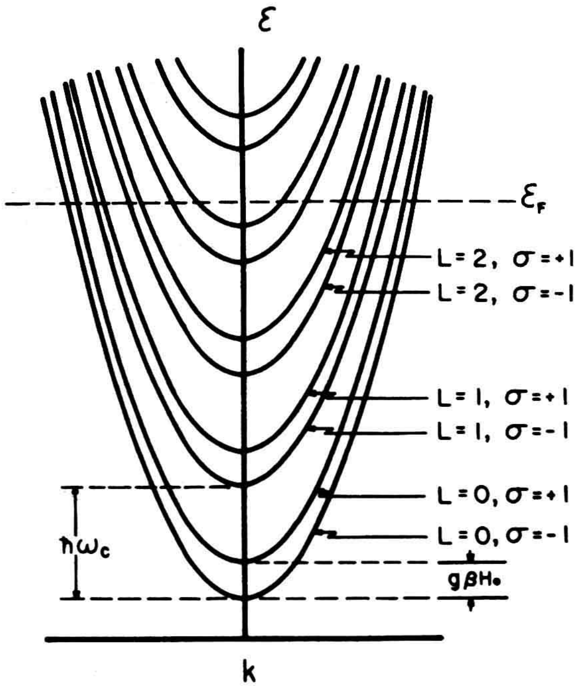

Fig. 1. One-dimensional "spherical" energy bands (Landau subbands) for an electron in a magnetic field.